CHARACTERISTICS OF THERMOCOUPLE ANEMOMETERS

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The problem of measuring the velocity of convection currents of air arising from temperature differences of a few degrees, is encountered in studies of processes involving heat transfer by convection. For example, in an iced refrigerator car filled with warm fruit the effectiveness of the ice in cooling the load is almost entirely dependent upon convection. Conduction and radiation are of only minor importance. The rate of movement of air is a principal controlling factor in refrigerator cars, refrigerated storages and in convection heated spaces of all kinds. Ordinary methods of measuring air flow are of little service for velocities of fractions of a foot per second or in air passages which are difficult or impossible to enter when readings are desired.

For the particular purpose of measuring air velocities under the floor racks of loaded refrigerator cars, an anemometer has been developed and found useful in many applications where other instruments cannot be used with complete satisfaction. It consists essentially of a thermocouple, both junctions of which are exposed to the air stream and one junction of which is heated. The difference in temperature between the junctions depends on the cooling effect of the moving air, and by suitable calibration, readings of the electromotive force of the thermocouple may be translated to air velocity.

Figure 1 shows the anemometer mounted on a hard rubber base with binding posts for connecting the leads. The thermocouple is of No. 24 B and S. gage copper and constantan wire. The constantan is but one inch

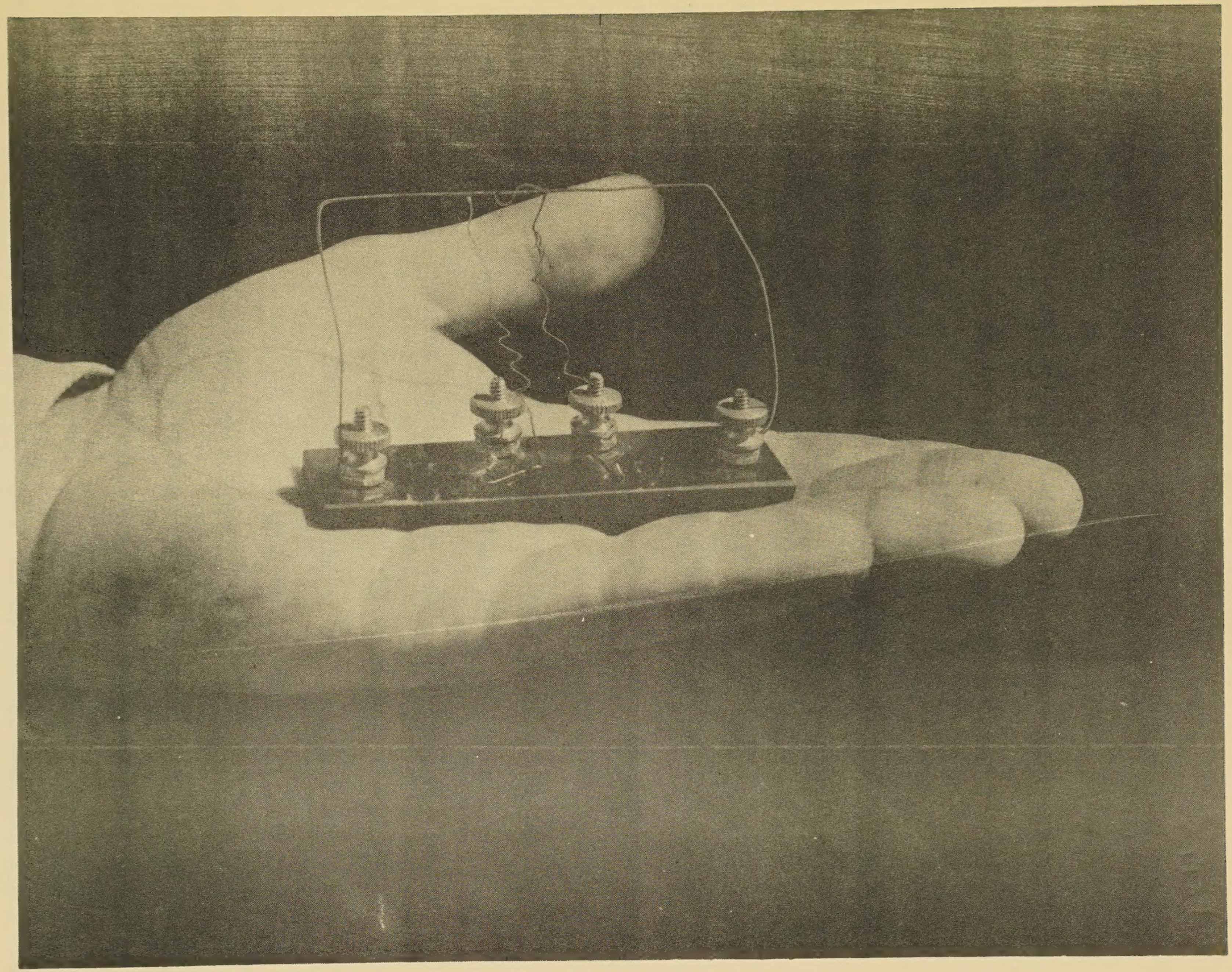

FIGURE 1

Thermocouple Anemometer, showing approximate size.

long and is butt jointed to the copper with silver solder making two junctions one inch apart. One of the junctions is wrapped with about 60 turns of No. 40 nichrome wire, through which an electric current of known amperage may be passed. Normally a current of about .05 ampere is used. In still air this current raises the temperature of the heated junction to about 50° F. above that of the cold junction and an electromotive force of one millivolt is set up in the thermocouple.

With this instrument velocities as low as six feet per minute may be measured. This lower limit may be reduced to between two and three feet per minute by modification of the construction. The anemometer may be set in position for reading and, with the lead wires extending as far as is desired, readings may be taken without the presence of an observer to disturb the air currents. For example, air velocities under the floor rack of a loaded refrigerator car are read with a potentiometer on the roof of the car so that it is not necessary to open the car doors or otherwise disturb conditions inside. Lead wires 50 to 100 feet long are commonly used to connect the anemometer to the potentiometer since the length does not affect the precision of the reading.

The anemometer is calibrated by moving it at known velocities on a whirling arm in still air. A typical calibration curve is shown in Fig. 2. It is found that the same relation between air velocity and thermocouple electromotive force exists for all individual instruments made in the same way, so that a common conversion chart can be used for all. On the other hand, the amount of heating current required for establishing the e.m.f.-velocity relation shown in figure 2 may not be the same for different individuals of apparently similar construction. This makes it necessary to

determine by test the amount of heating current required by each anemometer. It will be noted that the curve in figure 2 passes through 60 feet per minute at 650 microvolts. This has been chosen arbitrarily as the reference point. That is, when a new anemometer is to be put into use it is rotated in the calibrating chamber at a linear speed of 60 feet per minute. The current through the heating coil is adjusted until a reading of 650 microvolts is secured on the thermocouple terminals. This current is measured and the same amperage is used in all subsequent measurements of air velocity with that anemometer.

This type of anemometer has been in use for several years, and it is now possible to point out some of the characteristics which seem to be inherent in the instrument. Since one junction is at a temperature above that of the air it heats the air in contact with it and sets up a convection current. This is, of course, characteristic of any anemometer which uses cooling effect as a measure of air velocity. For this reason, a vertical air current does not have the same cooling effect as a horizontal current of equal velocity. Nor do upward and downward vertical currents have equal cooling effects. The calibration curve for horizontal velocities (fig. 2) therefore is only approximately correct for air currents moving upward or downward. The convection current set up by the heated junction appears to have a greater effect at low velocities (below 8 or 10 f.p.m.) than at higher velocities. It has been observed that when the velocity is below about 6 or 8 f.p.m. the thermocouple reading continually drifts over a small range even when the air stream is steady.

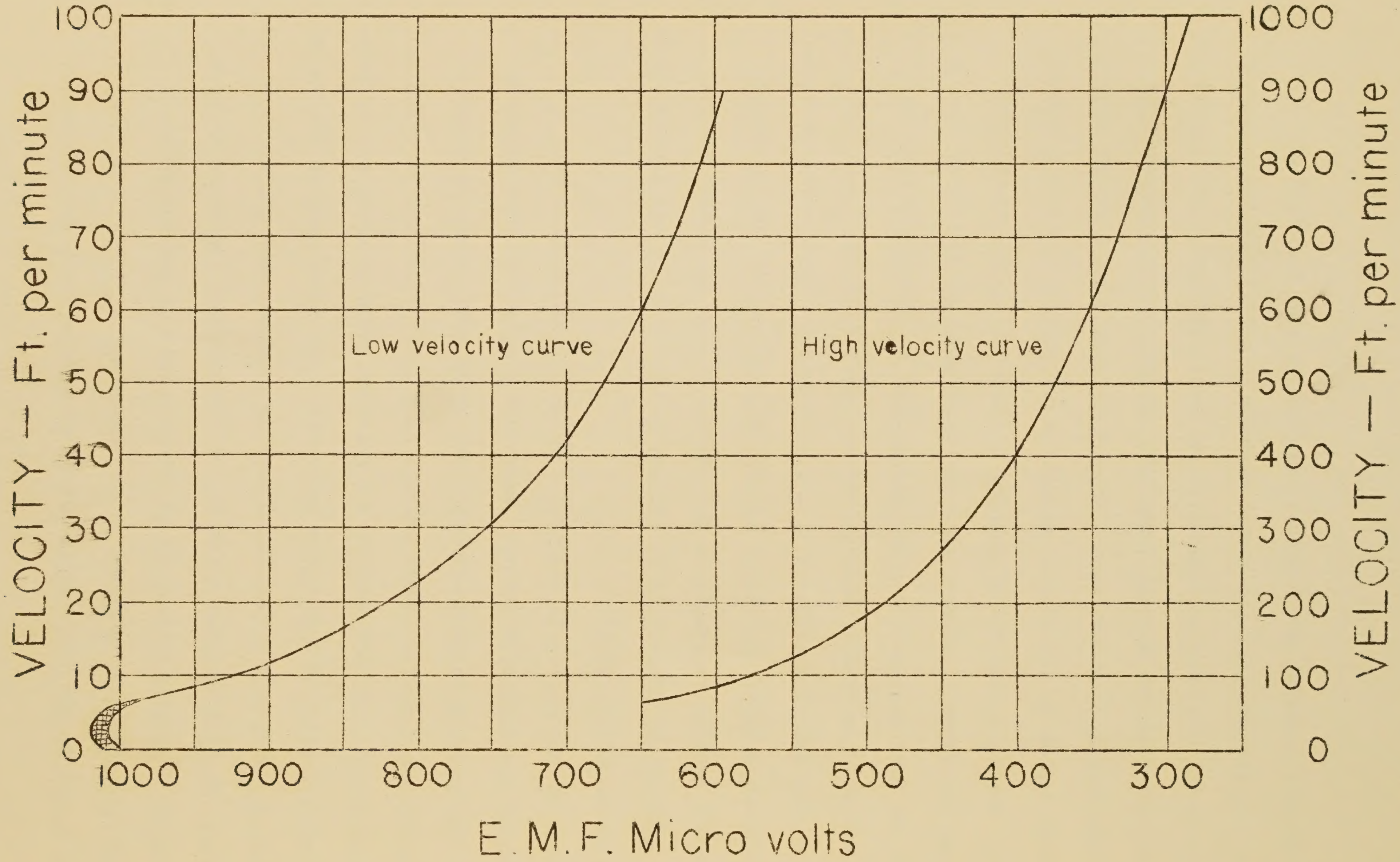

FIGURE 2

Relation between Velocity and Electromotive force for Thermocouple Anemometer.

The amplitude of the drift increases as the air velocity becomes lower. This is illustrated in figure 2 by the broadening of the line at low velocities. It will be noticed in figure 2 that as the air velocity decreases the electromotive force of the thermocouple increases until a velocity of about 2 or 3 feet per minute is reached, when further decrease in velocity results in a decrease in e.m.f. This shows that at extremely low velocities, increased general air movement tends to raise the temperature of the hot junction rather than to cool it. Since this is contrary to the effect which might be expected and which does obtain at higher velocities, the following possible explanation of the cooling effect at extremely low velocities is offered, although no experiments have been set up to prove its validity:

Suppose the anemometer is exposed to air which is not moving. When the heating current is turned on the temperature of the heated junction will rise and a small convection current will be set up, air in contact with the wire rising vertically in a smooth stream. This stream of air, being unbroken for an appreciable distance, will constitute a virtual chimney and will draw air past the heated wire in accordance with the height of the chimney effect. This air drawn past the wire will tend to cool it. Now if a very slight horizontal movement of air takes place the rising stream of air will be disturbed and broken into a less regular stream and displaced to one side. Accordingly the chimney effect will be lessened, and less air will be drawn past the wire by convection. The net movement of air past the wire will be the vector sum of the horizontal movement and the vertical convection movement. Slight horizontal movement apparently reduces the vertical movement to such a degree that the

net velocity past the wire is lower than if there were no horizontal movement. The minimum net velocity occurs when the horizontal velocity is about 2 or 3 feet per minute. At about 6 feet per minute (of horizontal movement) the horizontal component has increased enough that the net movement past the wire is about the same as with no horizontal movement. At higher velocities the convection effect becomes less effective although it may account for the drifting of the thermocouple reading at velocities somewhat higher than 6 f.p.m.

The above characteristic reversal of the cooling effect sets a minimum velocity, below which unique readings of velocity cannot be made. That is, the calibration curve shown extends to zero feet per minute but cannot be used for velocity measurements below 6 f.p.m. The reading at 4 f.p.m., for example, is about the same as at 1 f.p.m.

If it is desired to read velocities lower than 6 f.p.m. it is found that the minimum readable velocity can be lowered by reducing the heating current. For example, by using only one half the heating current the resulting calibration permits reading velocities down to about 4 f.p.m. This, however, is at the expense of reducing the temperature difference between the junctions to about one fourth of its original value, and therefore reducing the accuracy with which readings can be made.

The size of the wires affects the lower limit of readable velocities. By using #35 wire instead of #24 for the thermocouple and wire .0015" in in diameter instead of .0031" in the heating coil the limit is reduced to about 3 f.p.m. without any sacrifice in accuracy. This small type is difficult to construct and is very fragile. By using this small type and reducing the heating current so that the temperature difference between the hot and cold junctions is of the order of .3 millivolt, a usable calibration down to 2.2 f.p.m. has been obtained.

Any two metals having different thermo-electric powers can be used in the thermocouple. Copper and constantan are readily available in the proper size. Manganin was substituted for the copper in some. The thermo-electric power of manganin is about equal to that of copper, but its thermal conductivity is lower. When manganin is used less heat is carried away along the wire and a lower amount of heating current is required to maintain a given temperature difference between the junctions.

The cold junction of the thermocouple anemometer is immersed in the air stream to be measured. It, therefore, assumes a temperature approximately equal to that of the air. The thermocouple furnishes a measure of the rise in temperature of the heated junction due to the heating current. Since the e.m.f. per degree of a copper-constantan thermocouple changes slightly with changes in mean temperature it is to be expected that when the temperature of the air stream changes the characteristic relation between air velocity and thermocouple e.m.f. for a given heating current will be changed. It has been observed that such a change takes place. That is, if an anemometer has been calibrated in air at 80° F., that calibration will be only approximately correct at other temperatures. For many purposes the discrepancy may be neglected, but it should be recognized that there is a temperature correction. This difference in reading can be compensated by changing the amount of heating current. With an anemometer of the type whose calibration curve is shown in figure 2 it has been found that to give the e.m.f.-velocity relation illustrated in the figure, the heating current needs to be about 2 percent greater at 30° F. than at 80° F. air temperature. By measuring

the temperature of the air stream the proper adjustment of heating current may be made for reading the velocity. This correction, when demanded by a requirement for accuracy in readings, makes the operation of the instrument less simple. To avoid the necessity for reading the temperature and readjusting the heating current accordingly, a circuit for making this correction automatically has been devised. The circuit for the simple anemometer is shown diagramatically in figure 3, and that for the temperature compensated and standard current types in figure 4.

In Figure 3 the heating circuit is shown to consist of the heating coil which is wrapped on one junction of the thermocouple but not in electric contact with it, the battery, the standard resistor (across which the potential drop may be determined and used as a measure of the current flowing in the circuit) and the current adjusting rheostat. In using the instrument, the heating circuit is closed and an observation of the potential drop across the standard resistor is made with a potentiometer. The rheostat is adjusted until further observation of the potential drop indicates that the predetermined amount of current is flowing in the circuit. A reading of the electromotive force between the terminals of the thermocouple is then made, and by reference to a curve such as that in Figure 2, the air velocity measurement is completed.

The circuit shown in Figure 4 is similar to that in Figure 3 and readings are made in the same way. However, a shunt has been placed across the heating coil of such resistance that when a current of I_c which has the same value for all anemometers is passed through the standard resistor AB, the current, I_H, going through the heating coil is of the proper amperage for that particular anemometer. In addition, a temperature sensitive resistor, R_N, is placed in series with the heater coil so that if the temperature of the air stream is high, I_H will be reduced or if low, the current will be increased, in accordance with the changing current requirements at different ambient temperatures.

It has been found that with a copper-constantan thermocouple, size 24 B and S Gage, the current should be increased by one part in 2500 for each degree Fahrenheit drop in temperature in the range 30° F. to 80° F., the following equations showing the relations between the resistances and currents involved:

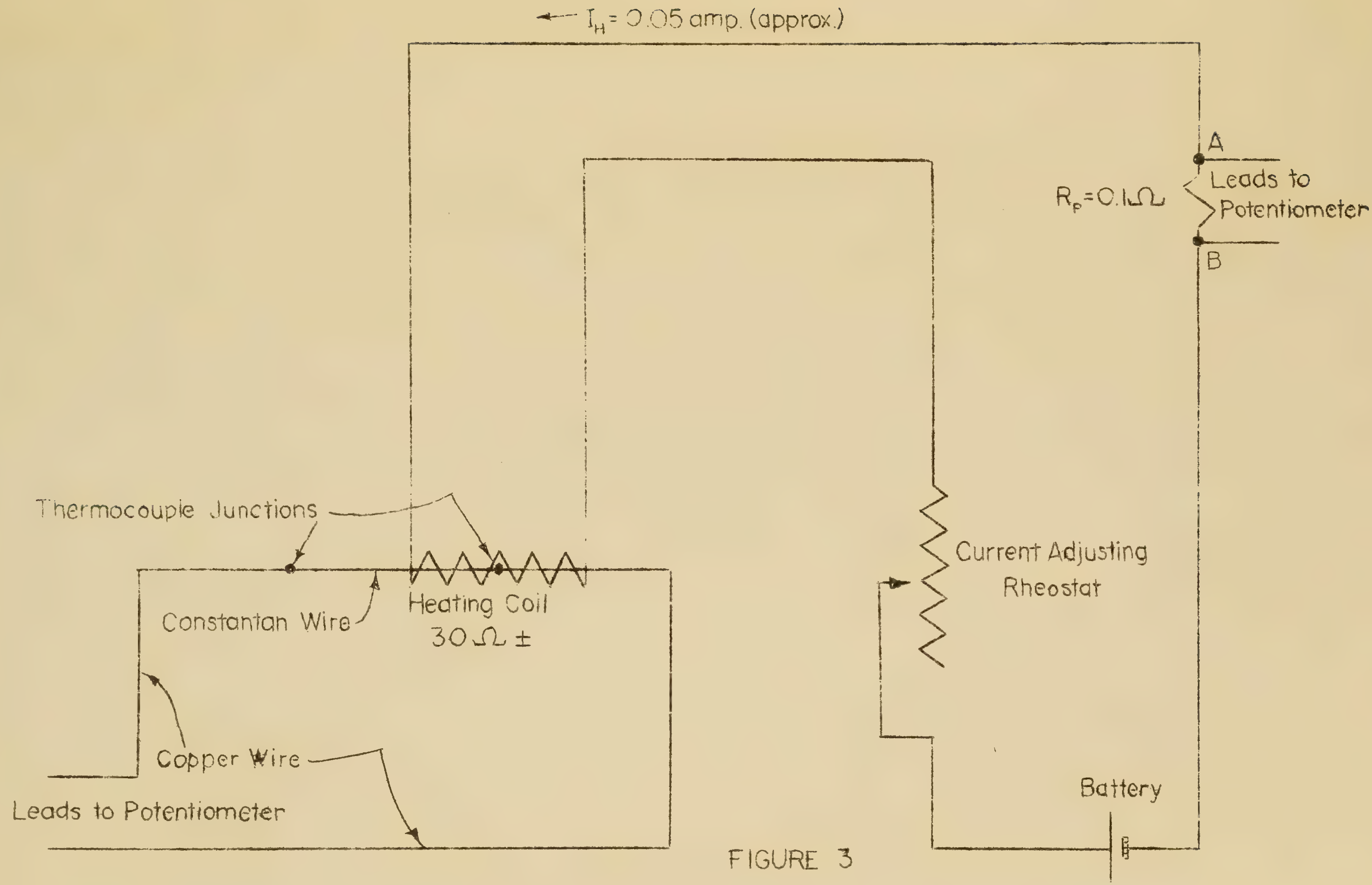

FIGURE 3

Simple Thermocouple Anemometer Circuit

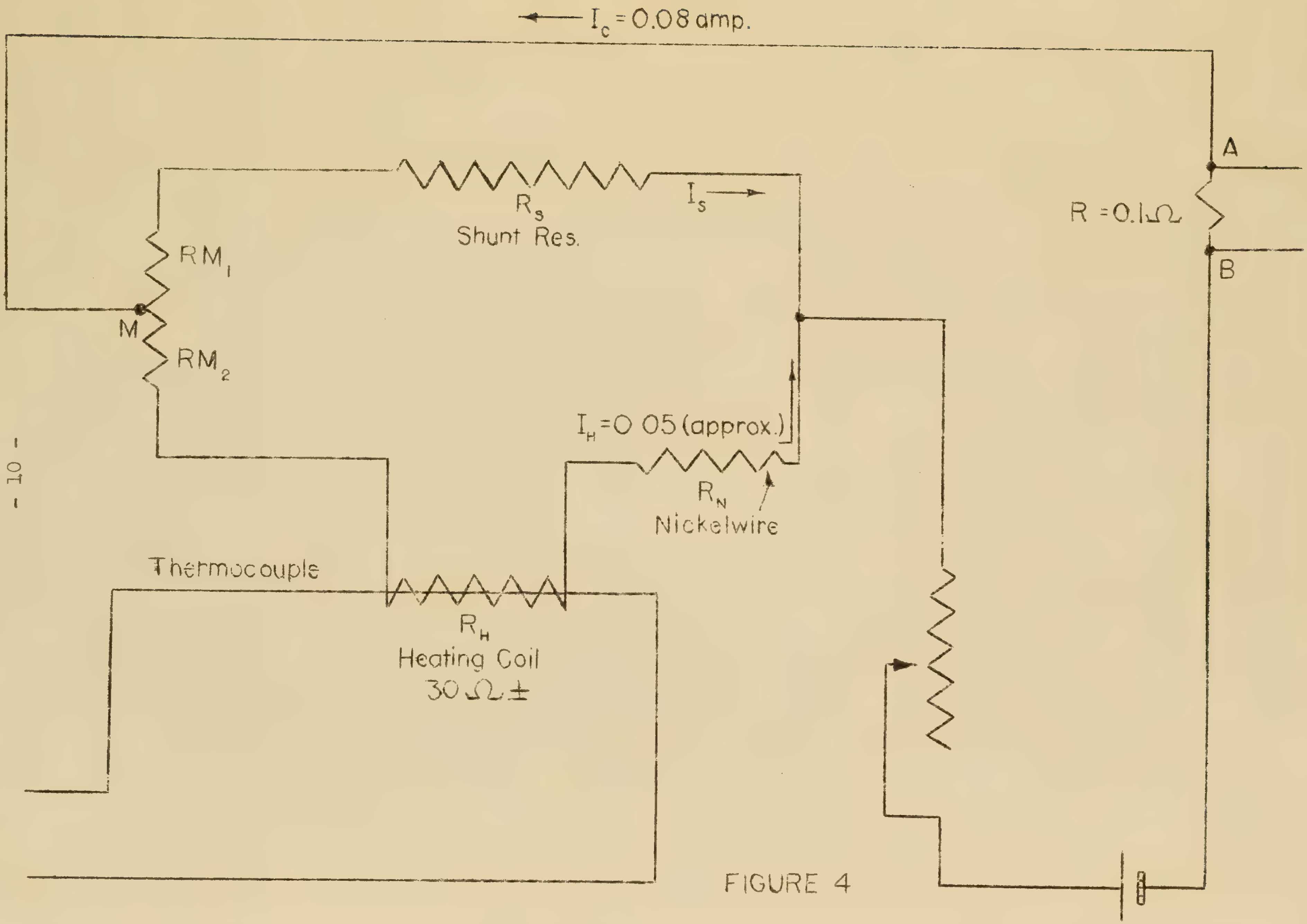

FIGURE 4

Thermocouple anemometer heating circuit for temperature compensation and standard current.

Referring to Figure 4, let R_s and R_{M1} be grouped together as R_1, and R_N, R_H, and R_{M2} be grouped as R_2 so that

$$R_1 = R_s + R_{M1}$$
$$\text{and } R_2 = R_N + R_H + R_{M2}$$
$$\text{then } I_H R_2 = I_S R_1 = (I_c - I_H) R_1$$

$$I_H = \frac{(I_c - I_H) R_1}{R_2}$$

$$I_H = \frac{I_c R_1}{R_2} - \frac{I_H R_1}{R_2}$$

$$I_H + \frac{I_H R_1}{R_2} = \frac{I_c R_1}{R_2}$$

$$I_H \left(1 + \frac{R_1}{R_2}\right) = \frac{I_c R_1}{R_2}$$

$$I_H = I_c \frac{R_1}{R_1 + R_2}$$

I_c may be considered constant since it is always brought to a standard value before a reading is taken. R_1 is the sum of R_s and R_{M1} and is constant once the location of point M is established for the anemometer. The heating current then is inversely proportional to the sum of all the resistances included in R_1 and R_2. From calibration at different temperatures, it is desired that the heating current increase one part in 2500 for each degree drop in the temperature of the air stream. If the amount of nickel wire (or other wire having a sufficient temperature coefficient of resistance) in R_N is so adjusted that the decrease in resistance of R_N for each degree drop in temperature is $\frac{1}{2500}$ part of the total, $R_1 + R_2$, the heating current will automatically increase by the same proportion. Since the range over which the anemometer is normally used is not over about 70° F. (from 30° to 100°) this reciprocal relationship gives adequate accuracy of temperature compensation.

In order to permit the use of a standard current I_c, the same for all anemometers, even though the heating current I_H may vary with different anemometers, the proper relation between I_c and I_H is obtained by adjusting the location of the contact M. This is done by trial while the instrument is moving in still air at known speed.

The circuit shown in figure 4 provides two modifications in operation. The temperature-sensitive resistance automatically applies a compensation for error due to the air-stream temperature; the shunt permits initial adjustment of each instrument so that even though different individuals require different heating current, the current supplied to the circuit may be made the same for all.

A number of characteristics of the thermocouple anemometer have not been investigated. No extensive tests have been made on the effects of air composition, for example, although calibrations made at high and low humidities indicate that moisture content of the air is of minor importance. Large percentages of carbon dioxide would no doubt affect the relation between air velocity and thermocouple reading, although no tests of this effect have been made.

The nature of the air motion, whether stream-line or turbulent, may also affect the anemometer reading.

All the above comments are based on experience in field and laboratory use and on calibration by one method only. This was by rotation at known velocities in still air in a tight box in which the possibility of convection currents was reduced to a minimum. Calibrating was done before the instrument was mounted for use. The question arose whether calibration by some other method would give different results. The calibration of one anemometer was tested in a tube in which the velocities were measured by a Thomas meter. At low velocities the agreement between the original calibration and the Thomas-meter corrected reading was not good. The anemometer calibration showed 9 f.p.m. in an air stream in which the Thomas meter showed 12.5 f.p.m. At higher velocities the percent difference between the readings

was less. The reason for this discrepancy has not been determined, but it is hoped that further calibration by other means will render the anemometer readings as accurate on an absolute basis as they appear to be on a relative basis. In spite of the lack of an absolute standard for checking the calibration of these instruments, they have proven useful in studies of air currents in refrigerator cars, storage houses, grain bins, and farmhouses in which heating tests are made, and in many cases have furnished data which were not obtainable with any other available instrument.